New color-octet axial vector boson revisited

Hao Wang [1], You-kai Wang [2,3] *, Bo Xiao [2], and Shou-hua Zhu [2,4]

[1] *The Department of Astronomy, Beijing Normal University, Beijing 100871, China*

[2] *Institute of Theoretical Physics & State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

[3] *Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

[4] *Center for High Energy Physics, Peking University, Beijing 100871, China*

(Dated: November 23, 2011)

Abstract

In this paper we reexamine how to utilize the previous proposed color-octet axial-vector boson $Z_{\rm C}$ to explain the 3.4σ anomaly of $t\bar{t}$ forward-backward (FB) asymmetry $A_{\rm FB}$ for $m_{t\bar{t}} > 450$GeV observed by CDF. Our numerical results indicate that the best-fit parameters are $g_A^q = 0.07$, $g_A^Q = 3$, and $M_{\rm C} = 440$GeV, which are obtained by fitting the mass dependent $A_{\rm FB}$ and total cross section data provided by a recent CDF measurement. Here $g_A^q(g_A^Q)$ and $M_{\rm C}$ are the axial couplings among $Z_{\rm C}$ with the first two (the third) generation quarks, and $Z_{\rm C}$ mass, respectively. We also calculate one-side forward-backward asymmetry $A_{\rm OFB}$ for top and bottom quark pair production at the LHC, focusing on the new contributions from $Z_{\rm C}$. Our studies show that $A_{\rm OFB}$ can be utilized to measure the properties of new particle $Z_{\rm C}$.

* wangyk@pku.edu.cn

I. INTRODUCTION

Recently, CDF and D0 measured the $t\bar{t}$ forward-backward asymmetry at the Tevatron and found an approximate 2σ deviation from the SM prediction [1–13]. In the latest CDF analysis [14], it is found that the measured $A_{\rm FB}$ is larger than the SM prediction by 3.4σ in the $M_{t\bar{t}} > 450$GeV region. These experiment results induced lots of new physics (NP) discussions [15–68].

Of all these NP explanations, one of the most discussed model is the t-channel Z'/W'/scalar model [15–48], where the NP particle Z'/W'/scalar induces a new t-channel $q\bar{q} \to t\bar{t}$. New asymmetric cross sections come from both the interference of the NP t-channel diagram with the SM gluon propagated s-channel diagram and the self-conjugation of the NP t-channel diagram. Contributions to the cross section from the above two resources have opposite sign, so an approximate cancelation of the new total cross sections can be achieved, which is required by the $t\bar{t}$ total cross section measurement. The t-channel neutral Z' model [15–21] is strongly restricted by the same-sign top quark pair production at the Tevatron[69, 70] and the LHC [15, 18, 19, 21–23, 71]; it is disfavored by the latest CMS [71] measurement of the same-sign top quark pair production at the LHC. W'/scalar is not sensitive to the same-sign top quark pair production, but can be easily tested (with only $\mathcal{O}(\text{fb}^{-1})$ of integrated luminosity) at the LHC though the $t\bar{t}+$jets channel [18, 19, 24–34].

Another kind of widely discussed NP is the s-channel color-octet axial-vector boson[16, 19, 49–66], where the new boson induces a new s-channel $q\bar{q} \to t\bar{t}$. The new asymmetric contributions can possibly come from the interference between the new s-channel diagram and the SM gluon propagated s-channel diagram, and from the self-conjugation of the new s-channel diagram. To generate positive extra asymmetric cross section, axial couplings with light and heavy quarks must have opposite sign ($g_A^q g_A^Q < 0$). The axigluon model, where the couplings of axigluon to light quarks and heavy quarks are both at the strong coupling level [19, 49, 50, 52, 53, 55, 56, 60, 62], is strongly constrained by the dijet [19, 34, 53–55, 58, 59, 72–76] measurements; indeed, the axigluon model proposed in [49] is already excluded by the latest dijet search by ATLAS [19, 76].

In the paper [64], part of us for the first time proposed a ~ 350GeV color-octet axial-vector boson $Z_{\rm C}$ to explain the top quark $A_{\rm FB}$ anomaly. $Z_{\rm C}$'s parameters are determined by the so called "above" and "below" mass dependent $A_{\rm FB}$ data, available at that time. $Z_{\rm C}$ is different

from the usually discussed $\mathcal{O}(1\text{TeV})$ heavy axigluon [19, 49–55] or KK-gluon [56–59] or other color-octet resonance [16, 54, 60–62] as its mass is near the top pair threshold. There are also some literatures [59, 77–79] which propose about hundreds GeV new color-octet axial-vector particles to explain the $A_{\rm FB}$ anomaly at the Tevatron. If the new particle's mass is still much larger than the top pair mass threshold, such as $700 \sim 800$ GeV in Ref.[59, 78, 79] or $\mathcal{O}(1\text{TeV})$ heavy axigluon, it must satisfy $g_A^q g_A^Q < 0$ to generate extra asymmetric cross sections. However, for the color-octet axial-vector boson $Z_{\rm C}$ in our previous paper[64] and $400 \sim 450$GeV axigluon in Ref.[77], the axial couplings to both light and heavy quarks can have the same sign because of the light mass near the top pair threshold. The difference between light axigluon in Ref.[77] and $Z_{\rm C}$ proposed by us is axigluon in Ref.[77] has flavor universal couplings to quarks and $Z_{\rm C}$ has flavor non-universal couplings. In the paper [65], we studied the possible explanation of both top $A_{\rm FB}$ and the dijet bump in the WZ/WW channel by adopting our proposed color-octet axial-vector boson $Z_{\rm C}$ and put the $Z_{\rm C}$'s mass $M_{\rm C} \sim 140$GeV. However we found that such parameters can not perfectly account for the recent CDF top $A_{\rm FB}$ mass dependent measurements, especially for the 3.4σ deviation for $M_{t\bar{t}} > 450$GeV. In this paper, we will focus on this issue and $Z_{\rm C}$'s parameters are fitted and contour diagrams are drawn, possible cross checks at the LHC are also discussed.

Our paper is organized as follows. Section II describes the feature of the $Z_{\rm C}$ model. In Section III we check the feasibility of this model in explaining the experiment, and obtain the constraints on the model parameters. Implications of this $Z_{\rm C}$ model at the LHC is discussed in Sec. IV, and we conclude in Sec. V.

II. MODEL DESCRIPTION

The squared matrix element of the $q\bar{q} \to t\bar{t}$ process with mediating a SM gluon or $Z_{\rm C}$ is

$$\begin{aligned}\sum_{\text{Color, Spin}} |M|^2 = \; & \tfrac{C_A C_F}{2}\{4g_s^4(1+c^2+4m^2) + \tfrac{8g_s^2\hat{s}(\hat{s}-M_{\rm C}^2)}{(\hat{s}-M_{\rm C}^2)^2+M_{\rm C}^2\Gamma_{\rm C}^2}[g_V^q g_V^t(1+c^2+4m^2) + 2g_A^q g_A^t c] \\ & + \tfrac{4\hat{s}^2}{(\hat{s}-M_{\rm C}^2)^2+M_{\rm C}^2\Gamma_{\rm C}^2}\,[8g_V^q g_A^q g_V^t g_A^t c + ((g_V^q)^2+(g_A^q)^2)\times \\ & ((g_V^t)^2(1+c^2+4m^2) + (g_A^t)^2(1+c^2-4m^2))]\},\end{aligned} \tag{1}$$

where q represents any of the light quarks; $m = m_t/\sqrt{\hat{s}}$, $\beta = \sqrt{1-4m^2}$, $c = \beta\cos\theta$; and $g_V^{q(t)}/g_A^{q(t)}$ are vector- and axial-vector couplings among light quarks (top) and $Z_{\rm C}$. $\Gamma_{\rm C}$ is the width of $Z_{\rm C}$. Terms on the right-hand side represent QCD amplitude self-conjugation, the interference between QCD and $Z_{\rm C}$ amplitudes and $Z_{\rm C}$ amplitude self-conjugation, respectively.

Equation (1) indicates that only odd c terms can contribute to the forward-backward asymmetry. To suppress the impact on the total cross section, it is reasonable to require the vectorlike couplings $g_V^q = g_V^t = 0$. So the new boson has a pure axial-vector coupling to the quarks [16, 50, 53, 54, 59, 61, 64, 65]. Under this assumption, Eq. (1) now becomes,

$$\begin{aligned}\sum_{\text{Color, Spin}} |M|^2 = \; & \tfrac{C_A C_F}{2}\{4g_s^4(1+c^2+4m^2) + \tfrac{8g_s^2\hat{s}(\hat{s}-M_{\rm C}^2)}{(\hat{s}-M_{\rm C}^2)^2+M_{\rm C}^2\Gamma_{\rm C}^2} 2g_A^q g_A^t c \\ & + \tfrac{4\hat{s}^2}{(\hat{s}-M_{\rm C}^2)^2+M_{\rm C}^2\Gamma_{\rm C}^2}(g_A^q g_A^t)^2(1+c^2-4m^2)\},\end{aligned} \tag{2}$$

in which the first term is the SM gluon mediated contribution, the second term is the interference between SM and $Z_{\rm C}$ process, which contributes to a nonezero asymmetric cross section, and the third term is the self-conjugation of the $Z_{\rm C}$ process, which may contribute to the total cross section.

From Eq. (2) one can see clearly that the product $g_A^q g_A^t$ must be large enough to generate an extra asymmetric cross section. On the other hand, g_A^q must be small in order to eliminate the extra contribution to the heavy quark and light dijet cross sections. So the axial couplings can be assumed as,

$$\begin{aligned} g_A^u = g_A^d = g_A^c = g_A^s \equiv g_A^q \\ g_A^b = g_A^t \equiv g_A^Q \end{aligned} \quad \text{with} \quad g_A^q < g_A^Q. \tag{3}$$

Therefore $\{g_A^q, g_A^Q, M_{\rm C}\}$ then form the complete free parameters set of the $Z_{\rm C}$ model. Note that here the third generation quarks now have an universal coupling g_A^Q with $Z_{\rm C}$, which is different from the assumption in our previous papers [64, 65]. In [64, 65], $Z_{\rm C}$'s coupling with bottom quark is set to be the same as those with the first two generation quarks. It will be convenient for the model construction for a generic third-generation coupling, as well as a larger coupling with bottom quarks will broaden $Z_{\rm C}$'s width $\Gamma_{\rm C}$, which makes it easier to be hidden in the invariant mass spectrum. g_A^b may be constrained from b physics, however, it can be expected that such constraints would be moderate due to the huge QCD

backgrounds. There will be a brief estimation based on the optimal fitted parameters in the following sections.

We shall check the feasibility of this model in explaining the latest experiments, and explore the experimental constraints on these parameters. This will be the content of the next section.

III. ANALYSIS

As mentioned in the above section, there are three independent parameters in the $Z_{\rm C}$ model, $\{g_A^q, g_A^Q, M_{\rm C}\}$. These parameters can be constrained by comparing experimental variables and their theoretical expected values at the Tevatron. Here the variables are adopted as the top pair total cross section $\sigma^{\rm tot}$, $(A_{\rm FB})_b$ with $M_{t\bar{t}}$ below 450GeV and $(A_{\rm FB})_a$ with $M_{t\bar{t}}$ above 450GeV.

Their explicit expressions can be listed as follows:

- Total cross section is a sum of the SM QCD and $Z_{\rm C}$ induced cross sections.

$$\sigma^{\rm SM+Z_C} = \sigma^{\rm SM} + \sigma^{Z_{\rm C}}, \tag{4}$$

  Here $\sigma^{Z_{\rm C}}$ is taken as its born level expression, as shown in the third term in Eq. (2). $\sigma^{\rm SM}$ is up to NLO QCD level.

- The asymmetry is contributed from both $Z_{\rm C}$ and SM QCD resources.

$$\begin{aligned}(A_{\rm FB}^{\rm SM+Z_C})_{a/b} &= \frac{(\sigma_A^{\rm SM})_{a/b}+(\sigma_A^{Z_{\rm C}})_{a/b}}{(\sigma^{\rm SM})_{a/b}+(\sigma^{Z_{\rm C}})_{a/b}} = \frac{(\sigma_A^{\rm SM})_{a/b}+(\sigma_A^{Z_{\rm C}})_{a/b}}{(\sigma^{\rm SM})_{a/b}} \frac{(\sigma^{\rm SM})_{a/b}}{(\sigma^{\rm SM})_{a/b}+(\sigma^{Z_{\rm C}})_{a/b}} \\ &\approx \left[(A_{\rm FB}^{\rm SM})_{a/b} + \frac{(\sigma_A^{Z_{\rm C}})_{a/b}}{(\sigma^{\rm LO})_{a/b}}\right] \frac{(\sigma^{\rm LO})_{a/b}}{(\sigma^{\rm LO})_{a/b}+(\sigma^{Z_{\rm C}})_{a/b}},\end{aligned} \tag{5}$$

  where σ_A is the asymmetric cross section, and the subscript a/b denotes that the $M_{t\bar{t}}$ are integrated above/below than 450GeV. Note that in the experiments, the SM expectation of the asymmetry is obtained from Monte Carlo generators, in which the denominator is taken as the NLO QCD cross section. It will be different with the usual theoretical calculation with a K factor [80], which is at order $K \sim 1.3$. We neglect this effect here.

TABLE I: Relative experimental results and SM expectations[14, 81] to obtain $\sigma^{\rm tot}$ and $(A_{\rm FB})_{a/b}$.

	$\sigma^{\rm tot}$	$(A_{\rm FB})_b$	$(A_{\rm FB})_a$	$(\sigma^{\rm LO})_b$	$(\sigma^{\rm LO})_a$
EXP	7.70 ± 0.52pb	-0.116 ± 0.153	0.475 ± 0.114	$\cdots$	$\cdots$
SM	$7.45^{+0.72}_{-0.63}$pb	0.040 ± 0.006	0.088 ± 0.013	3.70pb	2.23pb

For all the three variables, their one standard deviations are taken as the corresponding experimental errors. Some relative quantities are listed in Table I.

In our numerical calculation, the SM parameters are set as

$$\alpha_s(m_Z) = 0.118, m_t = 171.2\text{GeV}, m_b = 4.7\text{GeV}. \tag{6}$$

the renormalization and factorization scales are chosen as $\mu_R = \mu_F = m_t$; the PDF package CTEQ6L is used for the LO calculation and CTEQ6m is used for the NLO QCD calculation.

Generally speaking, there are two alternative methods to find the possible parameter region for $M_{\rm C}$. The first approach is to consider the constraint one by one independently, the second approach is to construct a total χ^2 by utilizing all inputs. We will use both methods in the following studies. It will be seen later that the two methods give the consistent results.

Figure 1 shows the contour diagram of the three independent constraints with $M_{\rm C}$ varying from 380 GeV to 485 GeV with a step of 15 GeV. The green/yellow area is the 1 σ allowed parameter region by requirement of the $A_{\rm FB}$ above/below $M_{t\bar{t}} = 450$ GeV. The area in the left region of the red curve is the allowed region from constraint from $t\bar{t}$ total cross section. The constraints can be understood by referring Eq. (2): For a lighter $Z_{\rm C}$ with its mass smaller than 450 GeV, it will be easy to induce the measured $A_{\rm FB}$ for $M_{t\bar{t}} > 450$ GeV but difficult for $M_{t\bar{t}} < 450$ GeV. The reason is that $\hat{s} - M_{\rm C}^2$ is more likely to be positive for $M_{t\bar{t}} < 450$ GeV, opposite to the measured central value of $A_{\rm FB}$. The opposite situation will happen when $M_{\rm C}$ is larger than 450 GeV, where $\hat{s} - M_{\rm C}^2$ is likely not large enough to produce enough asymmetric cross section and the product $g_A^q g_A^Q$ should be lager, out of the plotted region in Fig. 1. $Z_{\rm C}$'s impact on the total cross section will be always small, as can be seen in the third term in Eq. (2), so this constraint is not sensitive to the variation of the three parameters. After applying the three constraints, the overlapping region is 410 GeV $\lesssim M_{\rm C} \lesssim$ 455 GeV.

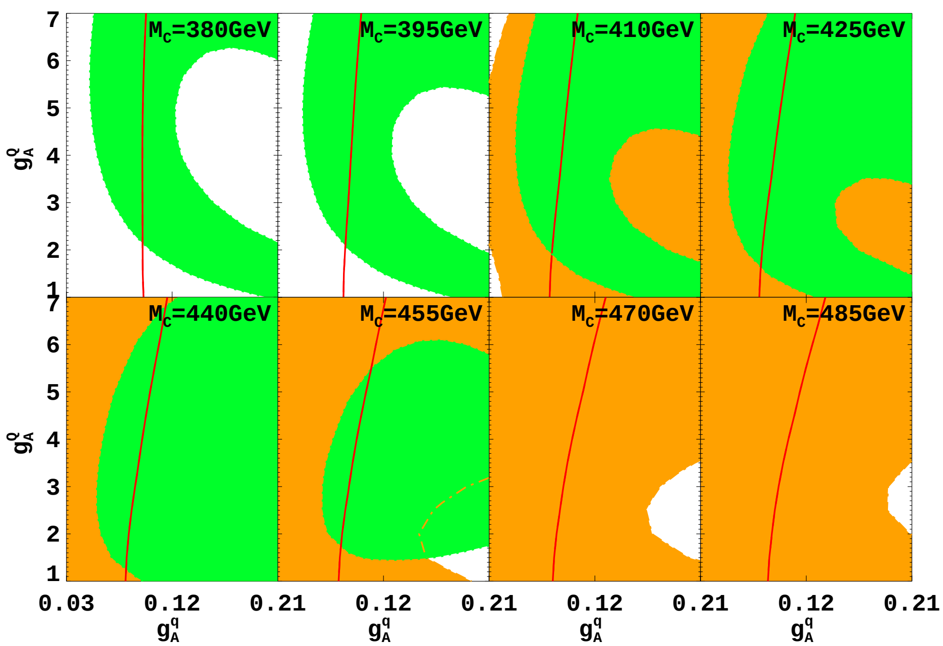

FIG. 1: The deviation contours on the $g_A^q - g_A^Q$ plane with different $M_{\rm C}$s.

The second method is the standard χ^2 fit, in which the χ^2 is defined as

$$\chi^2 \equiv \sum_i \frac{(O_i^{\rm th} - O_i^{\rm exp})^2}{(\delta O_i)^2}, \tag{7}$$

where O_i represents the three observables $\sigma^{\rm tot}$, $(A_{\rm FB})_a$ and $(A_{\rm FB})_b$. δO_i are taken as the corresponding experimental errors. A possible 3-dimension parameter region is scanned to find the minimal χ^2 point. Contour diagrams are obtained by the variation $\Delta\chi^2 \equiv \chi^2 - \min(\chi^2)$. In principle, such a χ^2 fit is not very suitable as there are too many free parameters and too few data samples. However, we make the χ^2 fit anyway and the situation may be improved in case of more statistics in the future. Figure 2 shows the two-dimensional contour diagrams with the other one parameter fixed at its optimal point. The best-fit parameters are $M_{\rm C} = 440$ GeV, $g_A^Q = 3.0$ and $g_A^q = 0.07$.[1] Limited by the accuracy of the Tevatron experimental data, large parameter space regions can still survive. For $M_{\rm C}$, it can vary from 390 GeV to 470 GeV within 1 σ deviation. $M_{\rm C}$ is somewhat greater than the

[1] By adopting these optimal parameters, we estimated the impact on R_b caused by $Z_{\rm C}$ in Z decay according to formulas in Ref.[55]. The vertex $Zb\bar{b}$ has about 0.4% correction and the corrected R_b agrees with SM predicted value within 1.2 standard deviation.

top pair threshold as the central value of $(A_{\rm FB})_b$ is negative. $Z_{\rm C}$'s axial-vector like coupling to the light quarks g_A^q is about $(0.04 \sim 0.12)$. The dijet constraints can be easily satisfied [40, 72–76] as comparing to the SM Z boson's couplings to the light quark ~ 0.36. Figure 1 shows that g_A^Q must be large, which indicates that $Z_{\rm C}$ maybe a condensate of the heavy quark pairs. Here we take g_A^Q as an effective coupling so the born level calculation in the $Z_{\rm C}$ model is still reliable.

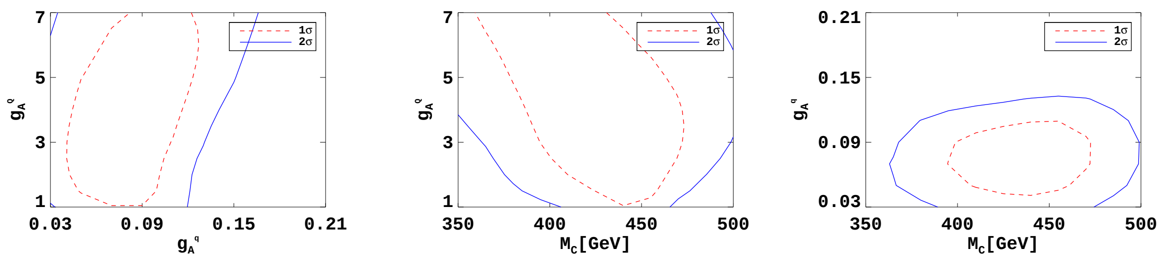

FIG. 2: Two-dimensional 1σ(red) and 2σ(blue) confidence regions of the new $Z_{\rm C}$ model, with the other one parameter fixed at its optimal point.

The expectations of the best-fit $Z_{\rm C}$ model, as well as the corresponding experimental measurements, for the mass dependent $A_{\rm FB}$ and the total cross section are listed in Table II. Comparing with Table I, one can see that by introducing $Z_{\rm C}$, the fit improves greatly and the anomaly between the theory and the experiment disappear, which are also illustrated in Fig.3. Figure 4 shows the impact of $Z_{\rm C}$ on the $d\sigma/dM_{t\bar{t}}$ distribution. A slight bump is introduced in the $d\sigma/dM_{t\bar{t}}$ distribution. However, due to its small size and the experimental uncertainty, this bump is hard to detect.

TABLE II: The experimental data and the $Z_{\rm C}$ model expectations of the total cross section, the $A_{\rm FB}$ in low and high invariant mass regions at the Tevatron.

	σ[pb]	$(A_{\rm FB})_b$	$(A_{\rm FB})_a$
EXP	7.70 ± 0.52	-0.116 ± 0.153	0.475 ± 0.114
SM+$Z_{\rm C}$	$8.12^{+0.72}_{-0.63}$	-0.089 ± 0.006	0.413 ± 0.013

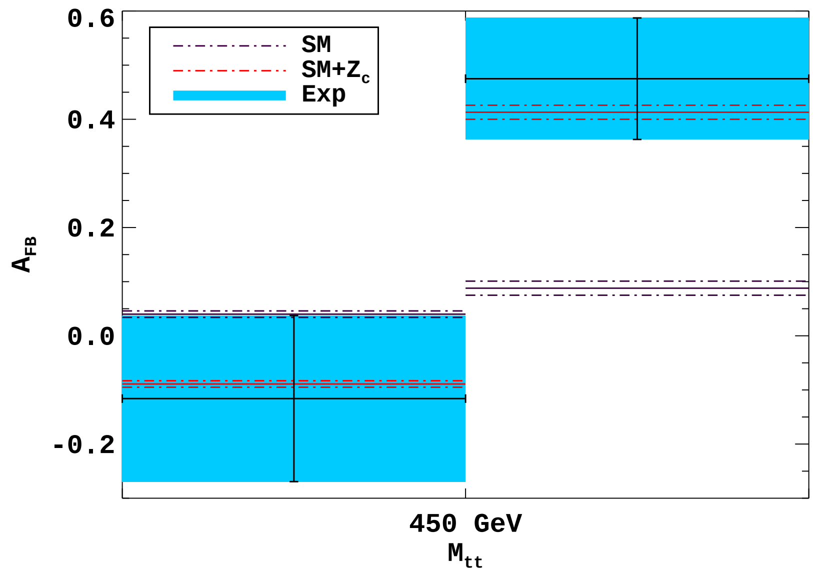

FIG. 3: Comparison of the mass dependent $A_{\rm FB}$ between the Tevatron experimental data[92], SM predictions and their theoretical value with the best-fitted $Z_{\rm C}$ parameters. Exact numbers can be found in Table I and Table II.

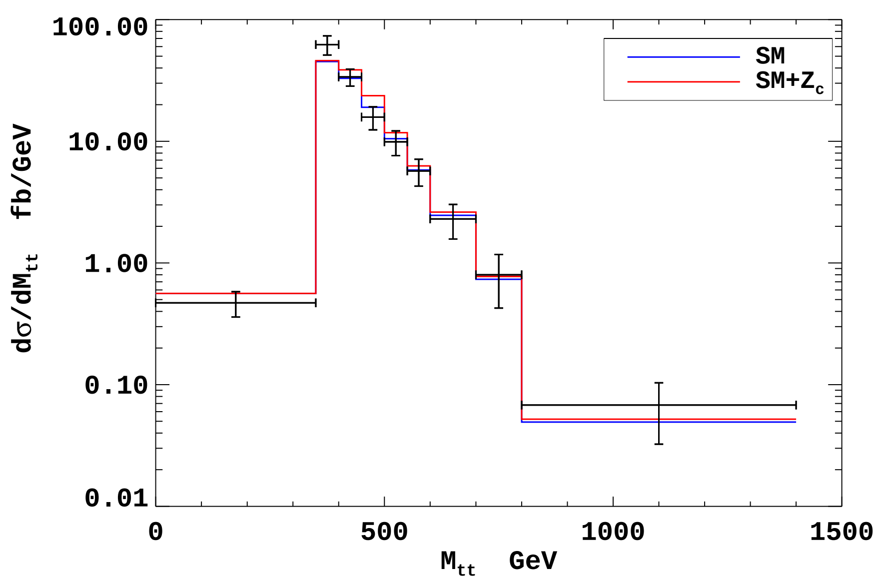

FIG. 4: Small bump near 450 GeV induced by $Z_{\rm C}$ on the $d\sigma/dM_{t\bar{t}}$ histograms. Tevatron experimatal data are taken from [92]. The SM predicted values are up to NLO QCD.

IV. THE IMPLICATIONS OF Z_C AT THE LHC

The top quark A_FB anomaly discovered at the Tevatron can be successfully explained by introducing the color-octet axial-vector-like boson Z_C. In this section, we will discuss how to study Z_C at the more powerful machine LHC. Discussions will be focused on on two kinds of final states, $t\bar{t}$ and $b\bar{b}$, as Z_C is assumed to couple strongly to third generation quarks.

Different from the $p\bar{p}$ collider Tevatron, there is no preferred direction at the charge-symmetric pp collider LHC. Various definitions of forward-backward asymmetry are proposed [6–8, 80, 82–90] to solve this problem. We make use of the so-called "one-side forward-backward asymmetry", A_OFB[80, 89], which is both conceptually transparent and observationally easy to detect.

The definition of A_OFB is:

$$A_\text{OFB} = \frac{F_- + B_-}{F_+ + B_+} \equiv \frac{\sigma^A}{\sigma}, \tag{8}$$

with

$$F_\pm = (\sigma(\Delta Y > 0) \pm \sigma(\Delta Y < 0))|_{P^z_{Q\bar{Q}} > P^z_\text{cut}} \tag{9}$$

$$B_\pm = (\sigma(\Delta Y < 0) \pm \sigma(\Delta Y > 0))|_{P^z_{Q\bar{Q}} < -P^z_\text{cut}} \tag{10}$$

where $\Delta Y = Y_Q - Y_{\bar{Q}}$ is the difference of rapidity between Q and $\bar{Q}$. P^z_cut is a cut on the longitudinal momentum $P^z_{Q\bar{Q}}$. The detailed definition can be found in Ref. [80].

Through our calculation, the SM parameters and PDF sets are chosen as in the last section (see Eq. (6) and the context therein), b-jet cut is taken as the transverse momentum $P^b_T > 20$ GeV and $Y < 2.5$, and the $t\bar{t}$ and $b\bar{b}$ detection efficiency are set as $\epsilon_{t\bar{t}} = 4\%$ and $\epsilon_{b\bar{b}} = 25\%$, respectively [91]. The energy of the LHC is set to be 7 TeV and an integrated luminosity of 10 fb^{-1} is assumed.

A_OFB as a function of P^z_cut for $t\bar{t}$ and $b\bar{b}$ final states are drawn in Fig. 5. Z_C's parameters are taken as their optimal values, $M_\text{C} = 440$ GeV, $g^Q_A = 3.0$ and $g^q_A = 0.07$. In order to exhibit the positive and negative values of A_OFB, we show the predicted A_OFB for $M_{Q\bar{Q}} > M_\text{C}$ and $M_{Q\bar{Q}} < M_\text{C}$ respectively. According to the error propagation formula, the statistical fluctuation of A_OFB can be expressed as

$$\delta A \equiv \sqrt{\frac{4N^F N^B}{N^3}} \simeq \frac{1}{\sqrt{\mathcal{L}\sigma\epsilon_{f\bar{f}}}}, \tag{11}$$

where N^F/N^B are the number of forward/backward events, and $N = N^F + N^B$ is the total events number. Error bars in Fig. 5 stand only for statistical uncertainties. It shows clearly that SM predictions are shifted significantly by effects of $Z_{\rm C}$.

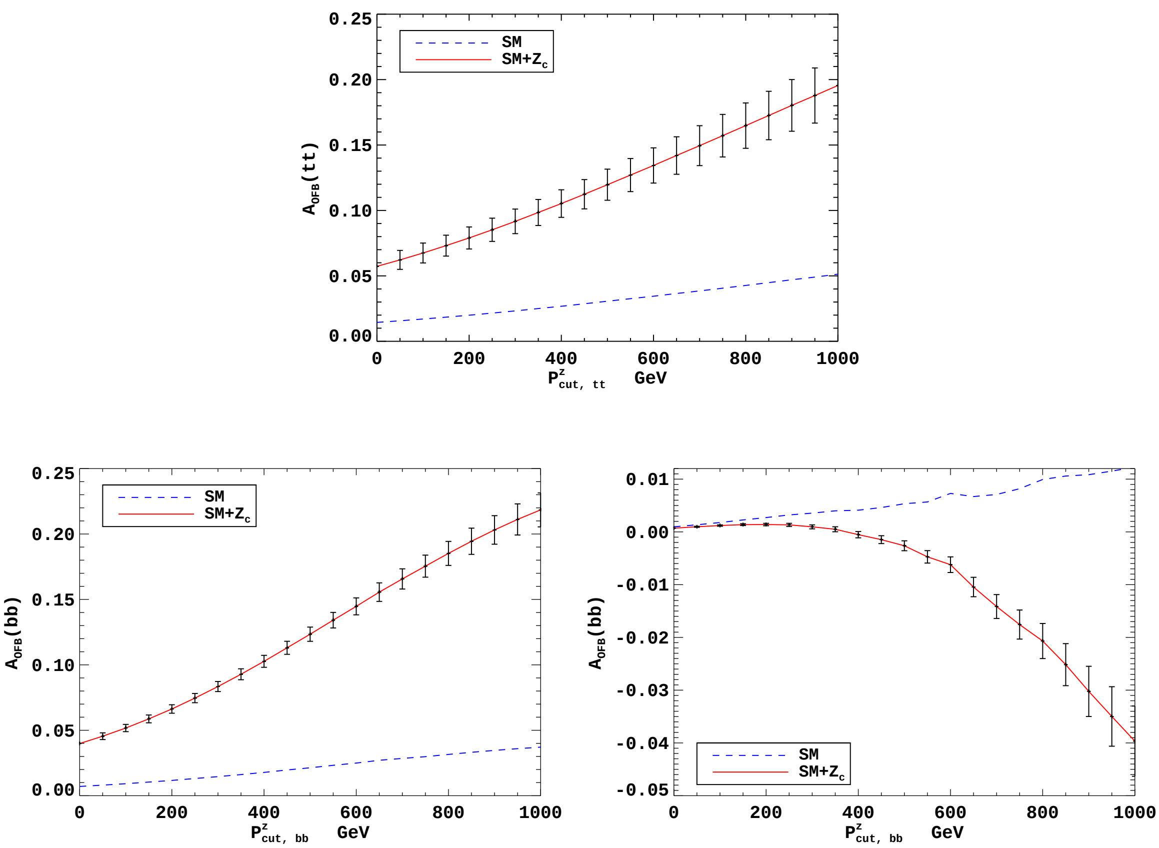

FIG. 5: SM and SM+$Z_{\rm C}$ expectations of the $A_{\rm OFB}(t\bar{t})$ and $A_{\rm OFB}(b\bar{b})$ as functions of the $P^z_{{\rm cut},t\bar{t}}$ at the 7 TeV LHC. In the top panel the $M_{t\bar{t}} > 440$ GeV cut is implemented; in the bottom left (right) panel the $M_{b\bar{b}} > 440$ GeV (100 GeV $< M_{b\bar{b}} <$ 440 GeV) cut is implemented.

As mentioned in the above section, $Z_{\rm C}$ can cause a negative sign $A_{\rm FB}$ in the $M_{Q\bar{Q}} < M_{\rm C}$ region, compared to the always positive $A_{\rm FB}$ for all energy regions in the SM. This is an interesting signature for $t\bar{t}$ or $b\bar{b}$ final states. Figure 2 shows that $M_{\rm C}$ can vary in an interval about $360 \sim 500$ GeV within 2 standard deviations. If $M_{\rm C} > 2m_t$, both $A_{\rm FB}(t\bar{t})$ and $A_{\rm FB}(b\bar{b})$ will be negative in the interval $2m_t < M_{Q\bar{Q}} < M_{\rm C}$. If $2m_b < M_{\rm C} < 2m_t$, $A_{\rm FB}(t\bar{t})$ will be always positive and $A_{\rm FB}(b\bar{b})$ will be negative in the interval $2m_b < M_{Q\bar{Q}} < M_{\rm C}$. This behavior can be used in checking the universal couplings of $Z_{\rm C}$ with the third-generation quarks. So it is crucial to measure the invariant mass dependent $A_{\rm FB}$ for both top and

bottom quark states to fix the location of the mass of Z_{C}.

Figure 6 shows the differential distributions for the quark pair producing cross section variate with the top and bottom quark pair invariant mass at the LHC with $s = 7$ TeV. For the bottom quark, $P_T^b > 20$GeV and $Y < 2.5$ cut is applied. Because of the dominate proportion of the $gg \to t\bar{t}/b\bar{b}$ channel, The bump caused by Z_{C} is almost completely neglectable compared to the SM background.

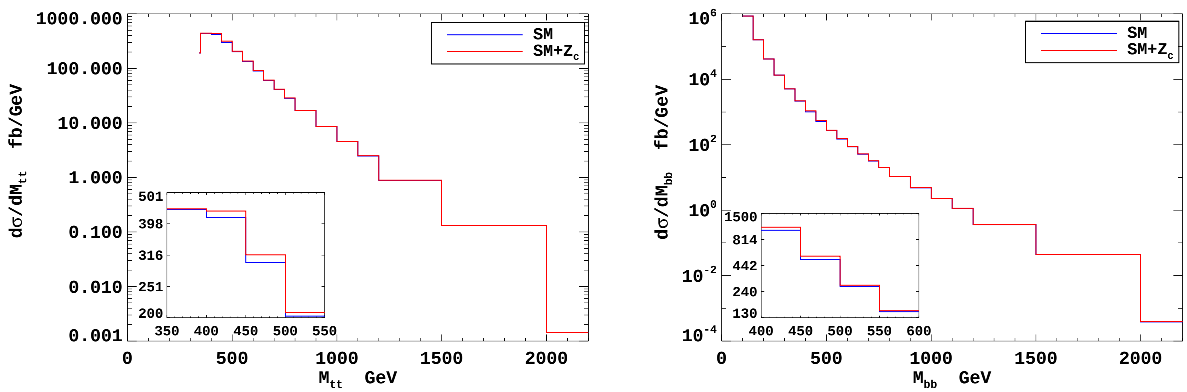

FIG. 6: Differential distributions of the total cross sections with the quark pair invariant mass. b quark cut is applied.

V. CONCLUSION AND DISCUSSION

In this paper we reexamine a color-octet pure axial-vector boson Z_{C} to account for the A_{FB} anomaly of the $t\bar{t}$ production at the Tevatron. Being a color-octet boson, Z_{C} is automatically leptonhobic, free from the di-lepton final state constraints. The pure axial-vector couplings of Z_{C} with quarks impact mainly on the quark angular distributions, rather than the total cross sections. Our studies show that Z_{C}'s mass is about hundreds GeV and couples to light and heavy quarks with different strength. The best-fit parameters are $M_{\mathrm{C}} = 440$ GeV, $g_A^q = 0.07$ and $g_A^Q = 3$. It can account for the measured A_{FB} excellently and at the same time has little impact on the two critical observables of $d\sigma/dM_{t\bar{t}}$ and dijet production. We also calculate A_{OFB} for top and bottom quark pair production at the LHC, focusing on the new contributions from Z_{C}. Our studies show that A_{OFB} can be utilized to measure the properties of new particle Z_{C}.

Acknowledgements: We would like to thank Martin Schmaltz for helpful discussions. This work is supported in part by the Natural Sciences Foundation of China (No. 11075003).

---

[1] V. M. Abazov *et al.*, (D0 Collaboration), Phys. Rev. Lett. **100**, 142002 (2008), arXiv:0712.0851.

[2] T. Aaltonen *et al.*, (CDF Collaboration), Phys. Rev. Lett. **101**, 202001 (2008), arXiv:0806.2472.

[3] CDF Collaboration, CDF Report No. CDF/ANAL/TOP/PUBLIC/9724, (2009).

[4] D0 Collaboration, D0 Report No. 6062-CONF, (2010).

[5] CDF Collaboration, Report No. CDF/ANAL/TOP/PUBLIC/10224, (2010).

[6] J. H. Kuhn and G. Rodrigo, Phys. Rev. **D59**, 054017 (1999), arXiv:hep-ph/9807420.

[7] J. H. Kuhn and G. Rodrigo, Phys. Rev. Lett. **81**, 49 (1998), arXiv:hep-ph/9802268.

[8] O. Antunano, J. H. Kuhn, and G. Rodrigo, Phys. Rev. **D77**, 014003 (2008), arXiv:0709.1652.

[9] W. Bernreuther and Z.-G. Si, Nucl. Phys. **B837**, 90 (2010), arXiv:1003.3926.

[10] G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos, and M. Worek, JHEP **02**, 083 (2011), arXiv:1012.4230.

[11] L. G. Almeida, G. F. Sterman, and W. Vogelsang, Phys. Rev. **D78**, 014008 (2008), arXiv:0805.1885.

[12] V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak, and L. L. Yang, JHEP **09**, 097 (2010), arXiv:1003.5827.

[13] V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak, and L. L. Yang, (2011), arXiv:1103.0550.

[14] T. Aaltonen *et al.*, (CDF Collaboration), Phys. Rev. **D83**, 112003 (2011), arXiv:1101.0034.

[15] S. Jung, H. Murayama, A. Pierce, and J. D. Wells, Phys. Rev. **D81**, 015004 (2010), arXiv:0907.4112.

[16] Q.-H. Cao, D. McKeen, J. L. Rosner, G. Shaughnessy, and C. E. M. Wagner, Phys. Rev. **D81**, 114004 (2010), arXiv:1003.3461.

[17] B. Bhattacherjee, S. S. Biswal, and D. Ghosh, Phys. Rev. **D83**, 091501 (2011), arXiv:1102.0545.

[18] S. Jung, A. Pierce, and J. D. Wells, Phys. Rev. **D83**, 114039 (2011), arXiv:1103.4835.

[19] J. Shu, K. Wang, and G. Zhu, (2011), arXiv:1104.0083.

[20] J. A. Aguilar-Saavedra and M. Perez-Victoria, Phys. Lett. **B701**, 93 (2011), arXiv:1104.1385.

[21] C. Degrande, J.-M. Gerard, C. Grojean, F. Maltoni, and G. Servant, Phys. Lett. **B703**, 306 (2011), arXiv:1104.1798.

[22] J. Cao, L. Wang, L. Wu, and J. M. Yang, Phys. Rev. **D84**, 074001 (2011), arXiv:1101.4456.

[23] E. L. Berger, Q.-H. Cao, C.-R. Chen, C. S. Li, and H. Zhang, Phys. Rev. Lett. **106**, 201801 (2011), arXiv:1101.5625.

[24] K. Cheung, W.-Y. Keung, and T.-C. Yuan, Phys. Lett. **B682**, 287 (2009), arXiv:0908.2589.

[25] J. Shu, T. M. P. Tait, and K. Wang, Phys. Rev. **D81**, 034012 (2010), arXiv:0911.3237.

[26] A. Arhrib, R. Benbrik, and C.-H. Chen, Phys. Rev. **D82**, 034034 (2010), arXiv:0911.4875.

[27] I. Dorsner, S. Fajfer, J. F. Kamenik, and N. Kosnik, Phys. Rev. **D81**, 055009 (2010), arXiv:0912.0972.

[28] K. Cheung and T.-C. Yuan, Phys. Rev. **D83**, 074006 (2011), arXiv:1101.1445.

[29] M. I. Gresham, I.-W. Kim, and K. M. Zurek, Phys. Rev. **D84**, 034025 (2011), arXiv:1102.0018.

[30] V. Barger, W.-Y. Keung, and C.-T. Yu, Phys. Lett. **B698**, 243 (2011), arXiv:1102.0279.

[31] B. Grinstein, A. L. Kagan, M. Trott, and J. Zupan, Phys. Rev. Lett. **107**, 012002 (2011), arXiv:1102.3374.

[32] K. M. Patel and P. Sharma, JHEP **04**, 085 (2011), arXiv:1102.4736.

[33] Z. Ligeti, G. M. Tavares, and M. Schmaltz, JHEP **06**, 109 (2011), arXiv:1103.2757.

[34] M. I. Gresham, I.-W. Kim, and K. M. Zurek, Phys. Rev. **D83**, 114027 (2011), arXiv:1103.3501.

[35] V. Barger, W.-Y. Keung, and C.-T. Yu, Phys. Rev. **D81**, 113009 (2010), arXiv:1002.1048.

[36] B. Xiao, Y.-k. Wang, and S.-h. Zhu, Phys. Rev. **D82**, 034026 (2010), arXiv:1006.2510.

[37] K. Blum *et al.*, Phys. Lett. **B702**, 364 (2011), arXiv:1102.3133.

[38] G. Isidori and J. F. Kamenik, Phys. Lett. **B700**, 145 (2011), arXiv:1103.0016.

[39] E. R. Barreto, Y. A. Coutinho, and J. Sa Borges, Phys. Rev. **D83**, 054006 (2011), arXiv:1103.1266.

[40] M. R. Buckley, D. Hooper, J. Kopp, and E. Neil, Phys. Rev. **D83**, 115013 (2011), arXiv:1103.6035.

[41] A. Rajaraman, Z. Surujon, and T. M. P. Tait, (2011), arXiv:1104.0947.

[42] C.-H. Chen, S. S. C. Law, and R.-H. Li, (2011), arXiv:1104.1497.

[43] A. E. Nelson, T. Okui, and T. S. Roy, (2011), arXiv:1104.2030.

[44] S. Jung, A. Pierce, and J. D. Wells, Phys. Rev. **D84**, 055018 (2011), arXiv:1104.3139.

[45] G. Zhu, Phys. Lett. **B703**, 142 (2011), arXiv:1104.3227.

[46] K. S. Babu, M. Frank, and S. K. Rai, Phys. Rev. Lett. **107**, 061802 (2011), arXiv:1104.4782.

[47] Y. Cui, Z. Han, and M. D. Schwartz, JHEP **07**, 127 (2011), arXiv:1106.3086.

[48] M. Duraisamy, A. Rashed, and A. Datta, Phys. Rev. **D84**, 054018 (2011), arXiv:1106.5982.

[49] P. H. Frampton, J. Shu, and K. Wang, Phys. Lett. **B683**, 294 (2010), arXiv:0911.2955.

[50] P. Ferrario and G. Rodrigo, PoS **DIS2010**, 191 (2010), arXiv:1006.5593.

[51] R. S. Chivukula, E. H. Simmons, and C. P. Yuan, Phys. Rev. **D82**, 094009 (2010), arXiv:1007.0260.

[52] M. V. Martynov and A. D. Smirnov, (2010), arXiv:1010.5649.

[53] D. Choudhury, R. M. Godbole, S. D. Rindani, and P. Saha, Phys. Rev. **D84**, 014023 (2011), arXiv:1012.4750.

[54] Y. Bai, J. L. Hewett, J. Kaplan, and T. G. Rizzo, JHEP **03**, 003 (2011), arXiv:1101.5203.

[55] U. Haisch and S. Westhoff, JHEP **08**, 088 (2011), arXiv:1106.0529.

[56] A. Djouadi, G. Moreau, F. Richard, and R. K. Singh, Phys. Rev. **D82**, 071702 (2010), arXiv:0906.0604.

[57] C. Delaunay, O. Gedalia, S. J. Lee, G. Perez, and E. Ponton, Phys. Lett. **B703**, 486 (2011), arXiv:1101.2902.

[58] A. Djouadi, G. Moreau, and F. Richard, Phys. Lett. **B701**, 458 (2011), arXiv:1105.3158.

[59] R. Barcelo, A. Carmona, M. Masip, and J. Santiago, Phys. Rev. **D84**, 014024 (2011), arXiv:1105.3333.

[60] P. Ferrario and G. Rodrigo, Phys. Rev. **D80**, 051701 (2009), arXiv:0906.5541.

[61] P. Ferrario and G. Rodrigo, JHEP **02**, 051 (2010), arXiv:0912.0687.

[62] G. Rodrigo and P. Ferrario, Nuovo Cim. **C33**, 04 (2010), arXiv:1007.4328.

[63] M. Bauer, F. Goertz, U. Haisch, T. Pfoh, and S. Westhoff, JHEP **11**, 039 (2010), arXiv:1008.0742.

[64] B. Xiao, Y.-k. Wang, and S.-h. Zhu, (2010), arXiv:1011.0152.

[65] X.-P. Wang, Y.-K. Wang, B. Xiao, J. Xu, and S.-h. Zhu, Phys. Rev. **D83**, 115010 (2011), arXiv:1104.1917.

[66] S. Westhoff, (2011), arXiv:1105.4624.

[67] A. R. Zerwekh, Phys. Lett. **B704**, 62 (2011), arXiv:1103.0956.

[68] D. Y. Shao *et al.*, (2011), arXiv:1107.4012.

[69] T. Aaltonen *et al.*, (CDF Collaboration), Phys. Rev. Lett. **102**, 041801 (2009), arXiv:0809.4903.

[70] CDF Collaboration, CDF/PHYS/EXO/PUBLIC/10466 (2011).

[71] S. Chatrchyan *et al.*, CMS, JHEP **08**, 005 (2011), arXiv:1106.2142.

[72] T. Aaltonen *et al.*, (CDF Collaboration), Phys. Rev. **D79**, 112002 (2009), arXiv:0812.4036.

[73] G. Aad *et al.*, ATLAS, Phys. Lett. **B694**, 327 (2011), arXiv:1009.5069.

[74] V. Khachatryan *et al.*, CMS, Phys. Rev. Lett. **105**, 211801 (2010), arXiv:1010.0203, [Publisher-note 106:029902,2011].

[75] V. Khachatryan *et al.*, CMS, Phys. Rev. Lett. **106**, 201804 (2011), arXiv:1102.2020.

[76] G. Aad *et al.*, ATLAS, New J. Phys. **13**, 053044 (2011), arXiv:1103.3864.

[77] G. M. Tavares and M. Schmaltz, (2011), arXiv:1107.0978.

[78] R. Barcelo, A. Carmona, M. Masip, and J. Santiago, (2011), arXiv:1106.4054.

[79] E. Alvarez, L. Da Rold, J. I. S. Vietto, and A. Szynkman, JHEP **09**, 007 (2011), arXiv:1107.1473.

[80] Y.-k. Wang, B. Xiao, and S.-h. Zhu, Phys. Rev. **D82**, 094011 (2010), arXiv:1008.2685.

[81] T. Aaltonen *et al.*, (CDF Collaboration), Phys. Rev. Lett. **105**, 012001 (2010), arXiv:1004.3224.

[82] P. Langacker, R. W. Robinett, and J. L. Rosner, Phys. Rev. **D30**, 1470 (1984).

[83] M. Dittmar, Phys. Rev. **D55**, 161 (1997), arXiv:hep-ex/9606002.

[84] F. Petriello and S. Quackenbush, Phys. Rev. **D77**, 115004 (2008), arXiv:0801.4389.

[85] R. Diener, S. Godfrey, and T. A. W. Martin, Phys. Rev. **D80**, 075014 (2009), arXiv:0909.2022.

[86] R. Diener, S. Godfrey, and T. A. W. Martin, Phys. Rev. **D83**, 115008 (2011), arXiv:1006.2845.

[87] P. Ferrario and G. Rodrigo, Phys. Rev. **D78**, 094018 (2008), arXiv:0809.3354.

[88] G. Rodrigo, PoS **RADCOR2007**, 010 (2007), arXiv:0803.2992.

[89] Y.-k. Wang, B. Xiao, and S.-h. Zhu, Phys. Rev. **D83**, 015002 (2011), arXiv:1011.1428.

[90] B. Xiao, Y.-K. Wang, Z.-Q. Zhou, and S.-h. Zhu, Phys. Rev. **D83**, 057503 (2011), arXiv:1101.2507.

[91] S. Godfrey and T. A. W. Martin, Phys. Rev. Lett. **101**, 151803 (2008), arXiv:0807.1080.

[92] T. Aaltonen *et al.*, (CDF Collaboration), Phys. Rev. Lett. **102**, 222003 (2009), arXiv:0903.2850.